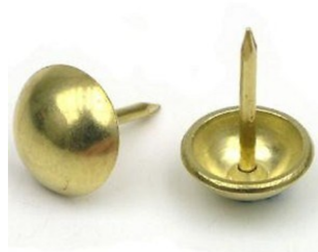
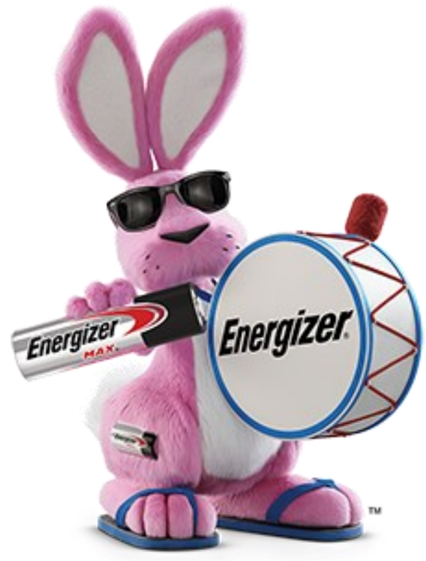
# Brass Tacks

***An in-depth look at a radio-related topic***



## How batteries work

Ever since the first viable battery was invented by Alessandro Volta, after whom the unit of electric potential was named, nearly every person on the planet is using or has used a battery, to supply electrical energy to a device, such as a flashlight, cell phone, or automobile. This article does not intend to explain the detailed differences between all the types of batteries available on the market today, such as Li-ion, AGM, $LiFePO_4$, and so forth, but rather showcase the fundamental ideas behind what makes batteries tick.

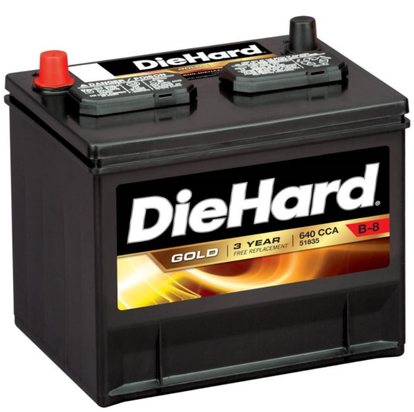



That being said, let's discuss two basic battery kingdoms that require different paths of exploration: ***rechargeable*** and ***non-rechargeable***. Obvious from their titles, a rechargeable battery can be restored to an energized state after its energy has been depleted, while a non-rechargeable battery cannot (and *should not*, in spite of some claims!)

## In general

Batteries work by chemical reaction, so that one chemical reacts with a metal (called the ***anode***, or negative "–" terminal), and *produces* electrons as a reaction by-product. If there's no place for the electrons to go, the reaction can only take place up to a point of *equilibrium*. Meanwhile, another chemical reacts with another metal (called the *cathode*, or positive "+" terminal), and *requires* electrons for its reaction to complete. And the reaction cannot take place there, until the needed electrons are provided.

The anode chemical reaction resulting in electrons and cathode chemical reaction resulting in electron requirement ("holes") produces an electric field, whose strength results in ***voltage***. The presence of the electric field, in turn, slows the chemical reactions, which reduces the electric field, and eventually both reach a point of equilibrium, which is fairly constant, and resulting in what we call the *open-circuit voltage*.




If we provide a pathway (wire, circuit, etc.) for the electrons in the anode reaction to flow to the cathode reaction, the electric field will be reduced slightly, both reactions can readily take place, and we now have a steady (chemically controlled, direct) current flow though the pathway, from the cathode side, through the pathway, and into the anode side. (Remember that *current flow* takes place in the opposite direction of *electron flow*.) If the battery chemical reactions are reversible, we call that battery *rechargeable*; otherwise, we call it *non-rechargeable*, to be discarded after most of the chemicals have reacted to present a workable electric field, and therefore, an acceptable voltage level.

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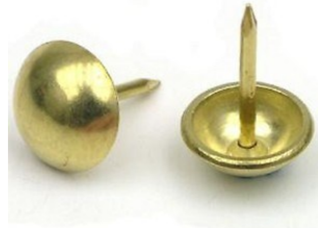


If we connect the anode of a battery charger, for example, to the rechargeable battery anode (and therefore, cathode to cathode), and the voltage presented by the charger is greater than that of the battery, current will flow out the cathode of the charger and into the cathode of the battery, reversing the chemical reactions and effectively *recharging* the battery.

Finally, a *cell* is a physical device in which these chemical reactions take place, and a *battery* is a collection of cells. However, the distinction is not important or relevant to this discussion, so we're going to assume they're one and the same. Besides, many devices that we call batteries are actually cells, and so they further blur the definition anyway.

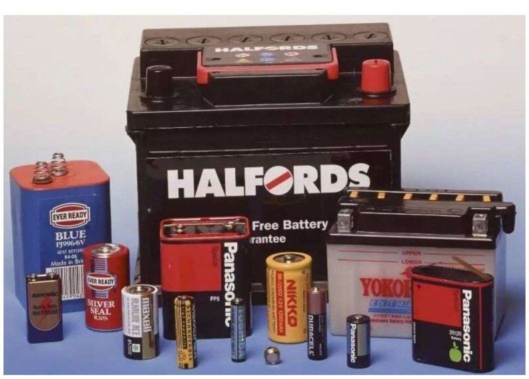
## Energy storage

Many are a little confused about what it is that a battery stores. Because a battery supplies electrical current, many believe that it stores *electrical energy*, but it doesn't. Because you must charge your (rechargeable) battery, some feel that it stores *charge*, but that's not what it stores either. As explained earlier, batteries work by chemical reaction, such that the greater the amount of reactants, the greater amount of energy that *can* be stored.

This means that a battery stores energy in its chemicals, also known as chemical energy, with the *potential* to complete the reaction and release the energy, given the right conditions. So, if you say that a battery stores chemical energy, you'd be correct; but, I like to say that it stores *electrochemical potential energy*, because a) it *can* deliver electrical energy originating from a chemical process, and b) it has the *potential* of delivering the energy slowly, like a firework fountain, or quickly, like a firecracker. Admittedly, this definition is not embraced by purists.

An important concept is that, as long as it's not broken and leaking chemicals, a battery weighs the same, holds the same amount of charge, and contains the exact same net amount of chemicals (but not the *same chemicals*, due to the reactions!), both when it's fully charged and when it's been discharged. Even the electrons that are produced by the anode reaction are consumed by the cathode reaction, resulting in a zero net electron gain and loss.

The only thing a battery gains or loses is the stored potential energy. For example, if my car is sitting on the road at the bottom of an easy-sloping hill, it has little useful potential energy. But if I push my car up to the top of that hill, it then has a lot more potential energy, or energy that is stored, and that I could potentially use later. But whether my car is at the top or bottom of the hill, it contained the same materials, and only differed by the potential energy, which could be released and used if I allowed it to roll down the hill.




## Battery voltage

The concept of voltage seems to be a vague concept for many, so let's define it within the grasp of the common folk. To continue the car-hill analogy, voltage is simply the difference in potential between being on top of the hill and being at the bottom of the hill, except that voltage is not truly energy. Voltage, technically, is *energy per unit charge*. As a result of its chemical reactions, each battery electrode presents an *electromotive force* (EMF), defined by the amount of

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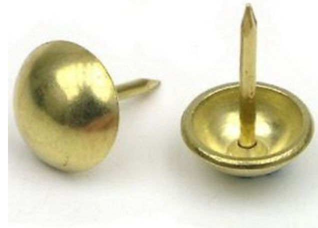

energy provided by the reaction divided by the amount of charge (electrons) that the reaction produces or requires. The difference between the EMF of the two electrodes is the battery *nominal voltage*.

The word *nominal* means "by name only," so that if you purchase a size "D" battery at the store, and discover at home that its voltage measures 1.495 volts, the battery isn't defective. Its nominal voltage is 1.5 volts because it's simply *called a 1.5 volt battery*, and 1.495 volts is within its expected tolerance range (± 5 %, for example.)

If I had rolled my car off that hill, it would probably have crashed into a wall at the bottom with a violent result. But the impact would probably have been even more spectacular if I had been able to roll my car from off an even higher hill. The difference between the impacts of the two situations onto the same wall determines the net impact of the entire experiment, and represents the potential (relative) damage difference on the wall (not to mention my car!)

## Rechargeable battery

Known also as a *secondary* type, we call a battery rechargeable if we're able to reverse the current flow to the battery, thereby reversing its chemical reaction direction. The only way to reverse the current flow direction is by raising the charging voltage higher than the battery voltage, with the positive charger terminal connected to the positive battery terminal. This causes the chemicals to *return* to their unreacted state, prepared to replay the reaction and once again allow electrons to flow, once a complete DC circuit is connected across the electrodes.

Here are some chemical reactions that take place in a rechargeable battery:

**Lead-acid (car) =** $Pb + PbO_2 + 2\ H_2SO_4 \leftrightarrow 2\ PbSO_4 + 2\ H_2O$

**Lithium-ion =** $LiC_6 + CoO_2 \leftrightarrow C_6 + LiCoO_2$

**$LiFePO_4$ =** $LiFePO_4 + C_6 \leftrightarrow LiC_6 + FePO_4$

**Ni-Cd (nicad) =** $Cd + NiO_2 + 2\ H_2O \leftrightarrow Cd(OH)_2 + Ni(OH)_2$

**NiMH =** $NiOOH + MH \leftrightarrow Ni(OH)_2 + M$ (replace "M" with Cu, Mg, Ti, Mn, Co, etc.)

One word of caution: not all rechargeable battery chargers can safely or reliably charge all rechargeable battery types. If you purchase an AGM (absorbed glass mat) or SLA (sealed lead-acid) battery, you must only use a charger that specifically states on its label or its manual that it was manufactured to charge an AGM or SLA battery, respectively. Some chargers can charge multiple types, but you need to be sure you're using the appropriate charger with the type of battery it was designed to charge, or you risk permanently damaging the battery.

A rechargeable battery must never be fully discharged; that is, you must ensure that the battery's electrochemical potential has not been completely exhausted. In fact, each rechargeable battery is specified by a maximum percent of discharge it can tolerate, called *depth of discharge* (DoD), to prevent damage. Not all rechargeable batteries can withstand the same depth of discharge, and care must be taken to not exceed this specification.

Batteries that are designed to tolerate a DoD of 50 % to 80 % (not a set or scientific level) are known as *deep-cycle batteries*. Many AGM batteries can tolerate up to 80 % DoD, while many marine-type batteries can tolerate 50 % DoD. These are both considered deep-cycle batteries,

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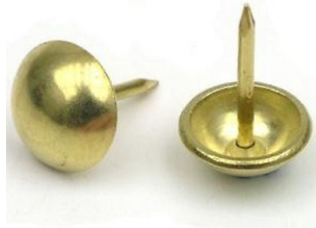

but not all AGM and marine batteries are deep-cycle types. If your application demands that your battery must be discharged heavily between charges, then a deep-cycle battery might be more appropriate for your needs.

There are applications (such as starting a truck with a large engine) in which you need to have a lot of electrical power delivered to a device in a relatively short period of time. These batteries are often referred to as *starting batteries*, and are usually mutually exclusive with deep-cycle batteries, although a few are labeled to both standards. The amount of rapid punch that a starting battery can deliver is listed in *cranking amps* (maximum current by a 12-volt battery at 0˚C for 30 seconds) or *cold-cranking amps* (maximum current by a 12-volt battery at 0˚F for 30 seconds.) The standard recommendation is 1 CCA (2 for diesel) per cubic inch of engine displacement. Typical battery values are 350 CCA for a 4-cylinder sedan and 850 CCA for a V-8 pickup truck.

The minimum charging voltage of a battery differs by battery type. The basic chemistry for most SLA batteries, for example, sets the operating voltage at 2.15 volts per cell. For a 6-cell battery, which advertises a nominal 12 volts, the battery will not charge if the charging voltage is below (6 x 2.15 volts = ) 12.9 volts. The maximum charging voltage of an SLA battery is about 2.35 volts per cell, or 6 x 2.35 volts = 14.1 volts.

A rechargeable battery will not remain fully charged indefinitely, even when no circuit is connected between its anode and its cathode. This is known as *parasitic loss*, and can vary by battery type, construction, and manufacture. The parasitic losses internal to a battery, such as surface film formation, particulate isolation, filament creation, and solid electrolyte interface buildup, are the chief sources of power loss in most Li-ion cells, for example. This differs from parasitic losses due to external reasons, because of connected circuits that draw a small amount of current, such as an LCD display (meter), a radio with an electronic power switch (which requires a tiny amount of standby power to turn it on), or a charger that's not charging.

## Non-rechargeable battery

Many chemical reactions that make up battery composition by their nature cannot be reversed, to return to their original chemical components. Technically known as a *primary* type, we also call them *disposable*, because they can only be discarded (or recycled) once they're expended. If you attempt to reverse-voltage a non-rechargeable battery in an effort to reverse the chemical process, you risk overheating the reactants, which could result in leakage due to reactant expansion, or even an explosion.

Here are some chemical reactions that take place in a non-rechargeable battery:

**Zinc-carbon** = $Zn + 2\ MnO_2 + 2\ NH_4Cl \rightarrow ZnCl_2 + Mn_2O_3 + 2\ NH_3 + H_2O$ + electrical energy
**Alkaline** = $Zn + 2\ MnO_2 + H_2O \rightarrow Mn_2O_3 + Zn(OH)_2$ + electrical energy
**Coin cell** = $Li + 2\ MnO_2^{4+} \rightarrow MnO_2^{3+}(Li^{+})$ + electrical energy

Non-rechargeable batteries are used where long storage times, high specific energies, and instant readiness are required. This is an interesting video of capacity caparisons of off-the-shelf non-rechargeable AA batteries, with some possibly surprising results. In spite of the growing popularity of rechargeable batteries, non-rechargeable types still hold an important role where charging might be impractical or impossible, such as military combat or fire-fighting.

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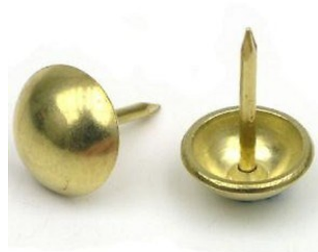

## Battery lifetime and disposal

Unlike diamonds, batteries don't last forever. Rechargeable batteries lose their ability to fully recharge, typically because of one or more of three reasons: 1) some of the reaction products solidify and become unavailable for further reaction, 2) the electrodes become coated with reactant by-products, and 3) the crystal lattice structure of metallic surfaces change into a semi-active or semi-conductive material. This is by no means an exhaustive list, and current research shows that there are indeed other reasons not widely known, such as current drift.

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Non-rechargeable batteries run out of juice because the amount of remaining reactants become insufficient to sustain a voltage level above a threshold of tolerance. This is why heating a battery (not recommended) or allowing one to sit for a few hours without being connected to a circuit, can *revive* the battery for a short while. Doing these might allow just enough of the reactions to take place, to raise the battery's voltage above the "dead" threshold for a little longer. I recommend replacing the battery ASAP, and disposing it properly instead.

There are published methods that claim to safely restore some life to a rechargeable battery, but I highly recommend you do some research on each method, to ensure its validity and reliability for your particular battery type. I'm not going to mention them here, because the results are too unproven to be reliable. In my opinion, you're better off discarding the old battery and purchasing a new one. As for non-rechargeable batteries, attempting to re-charge them or revive them can result in leakage, burns, or an explosion.

Besides their casing, batteries are made of the original chemical reactants, plus their reaction by-products. Some of these materials are fairly inert, but many are toxic. Once a battery is expended, if I toss it in the garbage, along with the chicken bones and watermelon rinds, it typically ends up in the county landfill. There, the casing eventually breaks down, and its hazardous contents spill out into the soil, and make their way down into our groundwater. The city water purification system can only affordably remove so much of the toxins, and the tiny but harmful molecules might just wind up in our drinking water.

I realize it's a chore, but I highly recommend you take expended batteries, rechargeable or otherwise, to an appropriate place of disposal, and not dump them into your trash can or dumpster. Many companies where you and I work have recycling bins for dead batteries. Some commercial vendors, such as Interstate Batteries will accept your rechargeable batteries for free and your non-rechargeable batteries for a small per-pound fee.

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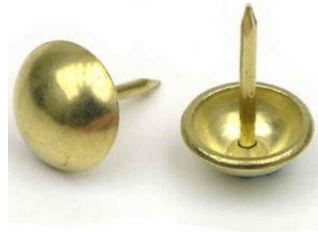

## Battery capacity

A battery can only hold so much potential, and then its chemical capacity becomes saturated. For example, if a battery only contained ten molecules of reactant and ten molecules of metal, whose reaction results in ten electrons from the anode reaction to the cathode reaction, once your battery receives all ten electrons back from one side of its reaction to the other, and all ten reactants are restored, your battery cannot be charged any further, no matter how long you left it on the charger. The *capacity* of this battery, then, is ten electrons, keeping in mind that a battery doesn't store charge; it only *moved* them.

To help communicate battery capacity between human beings, we've created a term called *amp-hour*, which is the *cheating* way to quantify charge, without using the word *charge*. A unit of charge is a very small quantity, so we use the term *coulomb* (named after a French physicist) to represent a large number of charges, namely 6.2415090744 x $10^{18}$ electrons, which is a lot. We say that if 1 coulomb of charge moves through a component in one second, we call that rate an *ampere*, which is defined as *1 coulomb of charge per second*.

So, if a battery can produce 1 ampere (amp) of current for one second, then the battery's capacity is (1 amp) x (1 second) = (1 coulomb/second) x (1 second) = 1 coulomb of charge. If a battery can produce 1 amp of current for one hour (3600 seconds), then the battery's capacity is (1 amp) x (3600 seconds) = (1 coulomb/second) x (3600 seconds) = 3600 coulombs. But it's more intuitive to leave the capacity at current x hours, or in this case, 1 amp-hour, abbreviated 1 Ah, or 1000 mAh. Therefore, a battery with a capacity of 3500 mAh can theoretically move 3500 mA of current in an hour, and can move up to (3.5 amps) x (3600 seconds) = 12,600 coulombs of charge. Or back to current convention (no pun intended), 3.5 Ah or 3500 mAh.

## Battery memory

All rechargeable batteries eventually lose some capacity due to repeated discharging and recharging. But some batteries, after having been only partially discharged, tend to become unable to discharge deeper than this partially discharged level. Known as the *memory effect*, it seems that they *remember* the level of discharge that was reached previously, and can no longer discharge to its specified DoD.

Knowing how costly (in terms of time and reliability, as well as money) battery memory was in the Ni-Cd battery days, many modern battery manufacturers still issue statements that assure potential buyers of the immunity to battery memory by their products.

## Summary

A battery is a device that stores electrochemical potential energy, which the chemicals convert into electrical energy if a circuit connects its two electrodes. Batteries are generally available in two flavors, rechargeable and non-rechargeable (disposable), but both types share several characteristics, such as how they store energy, how they expend energy, and how they produce voltage. Non-rechargeable batteries still have a useful place in society, where recharging is largely unavailable. Unfortunately, they both have lifetimes, thanks to physical limitations, and then proper disposal of expended batteries becomes a concern.

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